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Probing Cherenkov and Scintillation Light Separation for Next-Generation Neutrino Detectors

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Abstract. The ability to separate Cherenkov and scintillation signals in liquid scintillator detectors would enable outstanding background rejection for next-generation neutrino experiments. Reconstruction of directional information, ring imaging, and sub-Cherenkov threshold detection all have the potential to substantially improve particle and event identification. The Cherenkov-Scintillation Separation (CHESS) experiment uses an array of small, fast photomultipliers (PMTs) and state-of-the-art electronics to demonstrate the reconstruction of a Cherenkov ring in a scintillation medium based on photon hit times and detected charge. This setup has been used to characterize the ability to detect Cherenkov light in a range of target media. We show results with pure organic scintillator (LAB) and the prospects with scintillators with a secondary fluor (LAB/PPO). There are future plans to deploy the newly developed water-based liquid scintillator, a medium with a higher Cherenkov/Scintillation light yield ratio than conventional pure liquid scintillators, enhancing the visibility of the less abundant Cherenkov light in the presence of scintillation light. These results can inform the development of future large-scale detectors, such as the proposed THEIA experiment, or other large detectors at underground laboratories such as the far-site of the new Long Baseline Neutrino Facility at the Sanford Underground Research Facility. CHESS detector calibrations and commissioning will be discussed, and the latest results will be presented.

1. Introduction

Optical detectors for particle physics are usually designed to exploit one of the two most common detection techniques: Cherenkov or scintillation light. Detection of Cherenkov light in a scintillating medium strongly depends on the relative light yield, being very challenging for scintillators with a very high light yield. Successful separation in liquid scintillator would enable low-energy threshold detectors with direction reconstruction and an enhanced particle identification. Timing separation in liquid scintillator (LS) is theoretically possible using ultra-fast photon detectors, due to the longer scintillation time constants, but has never been realized in a large detector. Separation in water-based liquid scintillators (WbLS) [1] could potentially be enhanced based on the ability to tune scintillation light yield and time profile. This would permit construction of large, directional, low threshold detectors. We explore two different Cherenkov detection techniques: by time and by light density. The first one is applicable for high light yield LS while the second one strongly depends on the relative scintillation and Cherenkov light yield, and hence is better achieved in WbLS.



2. The CHESSE experiment

The goal of the CHESSE experiment is to demonstrate the separation of Cherenkov and scintillation light components in LS and WbLS using ultra-precise timing and charge information from an array of ultra fast timing PMTs (H11934-200). A schematic of the setup is in Fig.1. The principle is the following: a cosmic muon that passes through the liquid scintillator target produces Cherenkov and scintillation light which propagate through an acrylic medium towards the PMT array. Two scintillator tags allow selection of vertical-going muon events. The PMT array registers both the isotropic scintillation photons and the directional Cherenkov photons. Based on the refractive index of the target material, and thus the Cherenkov angle, there will be a set of PMTs hit by both scintillation and Cherenkov light and a set hit by pure scintillation. Radioactive sources can be deployed to provide ionization by multiple particle types with known energy spectra and test particle identification. The pulses from the fast PMTs are digitized using high sampling frequency flash digitizers (V1742) and stored for further analysis.

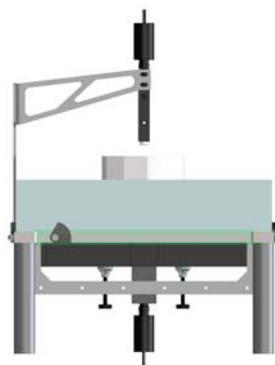


Figure 1. The CHESSE experiment on the left and a closer look of the fast PMT array for scintillation and Cherenkov separation on the right.

3. Water calibration

Cherenkov light produced in water is a well understood process that can therefore be used for calibrating the apparatus. A ^{90}Sr beta source is coupled to a water-filled target providing light for PMT gain and pulse shape calibrations. Another control sample used for further calibration of the cubic PMTs are cosmic muons passing through the acrylic block. They can be easily selected by requiring coincidence in the bottom cosmic tag and the bottom scintillator panel. Furthermore, Cherenkov rings in water produced by vertical muons can be identified, probing the principle of the setup and providing a measurement of the time precision. A complete Monte Carlo model is built using the RAT-PAC [2] suite, allowing setup optimization. Digitized PMT pulses are analyzed to estimate the number of photoelectrons by dividing the pedestal-corrected charge in the event window by the measured charge produced by a single photoelectron. The PMT hit time is defined as the time at which the PMT pulse crosses a threshold of 20% of the peak. The achieved time precision is $222 \pm 18\text{ps}$ FWHM, in very good agreement with the prediction of the calibrated MC simulation (Fig. 2).

4. Preliminary results with pure LAB

Performance of our setup on pure liquid scintillator is being studied before deploying WbLS. Pure Linear alkylbenzene (LAB) is used first due to its relatively low light yield and long time constants. The averaged number of photoelectrons detected in each PMT is shown in Fig. 3 for a total of 117 selected ring candidates. The number of detected photoelectrons is clearly larger for the outer PMTs, where the Cherenkov ring is expected. The inner and middle PMT hits are mainly due to scintillation light. The outer PMT hits are clearly earlier than the rest of the

PMT hits (Fig.2) showing a clear separation between Cherenkov and scintillation hits. Below 1 ns, at least 77% of the hits contain Cherenkov light, in good agreement with the simulation. Adding a secondary fluor to LAB increases the light yield and shortens the light emission time, making the Cherenkov separation very challenging. We plan to demonstrate Cherenkov separation with a mixture of LAB and PPO. Expected performance of a cocktail with 2 g/L of PPO in LAB is predicted using Monte Carlo assuming the light yield and time constant measured in [3]. We expect to achieve a Cherenkov separation of 70% based on photon hit times (Fig.2).

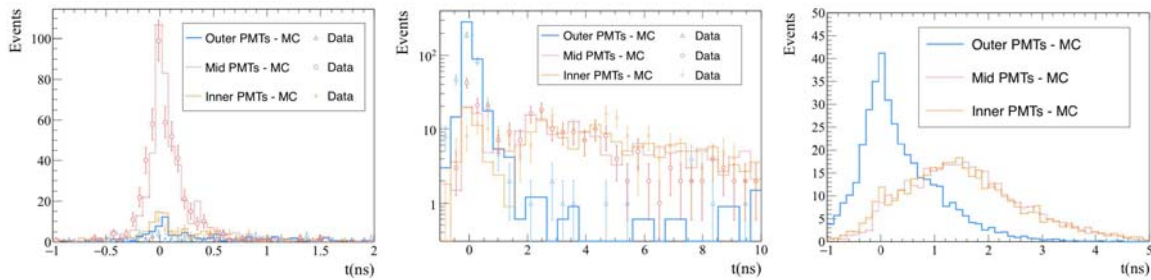


Figure 2. Timing distributions for each PMT, grouped by radius. Water data on the left, pure LAB in the center and the projected distribution for LAB/PPO on the right

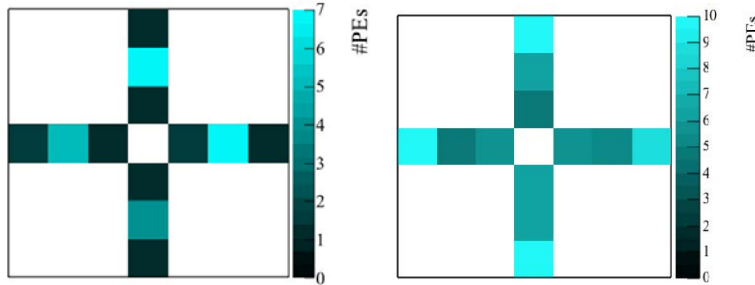


Figure 3. Number of photoelectrons for a single ring candidate in water on the left and the averaged number of photoelectron for all the selected rings candidate for pure LAB on the right.

5. Conclusion and outlook

CHESS has demonstrated a clear time separation of the Cherenkov and scintillation light in pure LAB. Monte Carlo simulation predicts a clear separation in a LAB/PPO cocktail. WbLS will be deployed and characterized once that the principle has been proven in pure LS. This is a first step towards the proposed 100kT WbLS THEIA [5], a large monolithic optical detector that would enable a broad physics portfolio including neutrino-less double beta decay, solar neutrinos and, if located in a neutrino beam, CPV and neutrino mass hierarchy measurements [4].

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